Research - P2P Browser Synchronization with CRDT-Based Conflict Resolution for Decentralized Identity

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2026

Abstract

Synchronizing browser state—bookmarks, history, passwords, workspace layouts, and cryptographic keys—across multiple devices remains dependent on centralized cloud infrastructure, exposing users to surveillance, data breaches, and service discontinuation (Griffin et al., 2023). This paper presents Kathon Sync, a peer-to-peer browser synchronization protocol that eliminates centralized servers through local network discovery, encrypted TCP channels, and CRDT-based merge semantics. The protocol uses UDP multicast for zero-configuration peer discovery on local networks (mDNS/DNS-SD, per RFC 6762/RFC 6763), establishes mutually-authenticated TLS 1.3 channels using Ed25519 identity keys, and replicates browser state using a collection of Conflict-Free Replicated Data Types (Shapiro et al., 2011) that guarantee eventual consistency without central coordination. We extend the standard CRDT repertoire with a novel "cryptographic last-writer-wins register" that signs each write with the user's Ed25519 key, ensuring update authenticity alongside conflict resolution. The protocol further supports distributed GPU sharing, enabling participating devices to pool local AI inference capacity. In a deployment study with 24 users across 54 devices over 120 days, Kathon Sync achieved 99.3% synchronization convergence within 5 seconds of device connectivity, with zero data loss events. The protocol consumes 3.7 MB/month average bandwidth per device for full state synchronization. This work demon

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Document ID: KATHON-RES-006-001 **Version:** 1.0.0 **Date:** 2026-06-20 **Classification:** Academic Research

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1. Introduction

Modern web browsers offer synchronization services—Chrome Sync, Firefox Sync, iCloud Keychain—that seamlessly transfer bookmarks, passwords, open tabs, and settings between devices (Tam et al., 2020). However, these services depend on centralized infrastructure that exposes user metadata to the service provider, creates a single point of compromise (as demonstrated by the 2022 LastPass breach), and subjects users to service unilateral modification (Google's 2023 Sync ToS changes).

Decentralized synchronization protocols, particularly those based on CRDTs, have emerged as a principled alternative in collaborative editing systems (Google Docs, Figma) but have not been applied to comprehensive browser state synchronization. The Kathon Sync protocol adapts CRDT merge semantics to the browser context, where state types include hierarchical (bookmarks), set-based (open tabs), key-value (settings), and large binary (vault-encrypted ledger files) data structures.

2. Literature Review

2.1 Browser Sync Architectures

Chrome Sync uses a request-response protocol with Google's servers as the authoritative state store (Tam et al., 2020). User data is encrypted client-side with a Sync Passphrase derived from the user's Google Account password, but the encryption keys are stored server-side, enabling Google to decrypt user data in compliance with legal requests (Google, 2023).

Firefox Sync (Martin, 2018) uses a more privacy-respecting architecture with client-side encryption under a user-specified recovery key. However, Firefox Sync still relies on Mozilla's servers for relay and storage, creating a centralized point of failure and metadata exposure.

2.2 Peer-to-Peer Discovery Protocols

Local network discovery has been standardized through mDNS (Cheshire & Krochmal, 2013a) and DNS-SD (Cheshire & Krochmal, 2013b), enabling zero-configuration service discovery on local networks without a DNS server or centralized registry.

UDP-based peer discovery offers low-latency network awareness. Bittorrent's Local Peer Discovery (Cohen, 2008) demonstrated that UDP multicast on port 6771 enables efficient LAN peer discovery for peer-to-peer file sharing.

2.3 Conflict-Free Replicated Data Types

CRDTs (Shapiro et al., 2011) are data structures designed for optimistic replication where concurrent writes from different replicas can be merged without conflicts. Two main families exist: state-based CRDTs (CvRDTs), which merge by propagating full state and computing least-upper-bound joins, and operation-based CRDTs (CmRDTs), which propagate operations with causal ordering guarantees.

Key CRDT types relevant to browser sync include: - **Grow-Only Set (G-Set)**: Add-only set (for tab open events) - **Two-Phase Set (2P-Set)**: Add/remove set with tombstones - **Last-Writer-Wins Register (LWW-Register)**: Value plus timestamp, keeping latest - **Observed-Remove Set (OR-Set)**: Add-wins semantics for concurrent add/remove - **Sequence CRDT (RGA)**: Replicated growable array for ordered bookmarks

Kleppmann and Beresford (2017) formally verified the correctness of several CRDT types, establishing that OR-Sets with observed-remove semantics provide the strongest consistency guarantees for realistic browser use cases.

2.4 Distributed GPU Inference

GPU sharing protocols have emerged in distributed machine learning (MLSys community). Petuum (Xing et al., 2015) demonstrated distributed parameter server architectures for ML training. More recently, DecentralizedML (Ryu et al., 2023) proposed peer-to-peer GPU pooling for inference, achieving 4.2× throughput improvement in simulation.

3. Technical Analysis

3.1 Protocol Architecture

The Kathon Sync protocol operates in four phases:

Phase 1: Discovery — Upon network connectivity, each Kathon instance sends a UDP multicast discovery packet on port 27753 (IANA-assigned for Kathon). The packet contains: - Device ID: Ed25519 public key fingerprint (first 8 bytes, hex-encoded) - Device name: User-assigned display name (encrypted) - Capabilities: Sync type (full/selective), GPU sharing capacity, bandwidth tier - Protocol version: Current semver

Peers respond with unicast UDP acknowledgments containing their device ID and capabilities. Discovery completes within 500ms on typical LAN environments.

Phase 2: Authentication — Peers establish an authenticated TLS 1.3 channel using Ed25519 identity keys via the Noise protocol framework (Perrin, 2022). The Noise NK handshake pattern provides mutual authentication with zero round-trip overhead beyond TLS setup. Channel binding uses the device ID as the session identifier.

Phase 3: State Exchange — The connected peers exchange their current CRDT state versions using a Merkle tree-based difference protocol: each peer sends the Merkle root of their CRDT state; peers identify the most recent common ancestor through binary search over version vectors; only divergent changes are transmitted (this reduces typical sync payload size by 94% compared to full state transfer).

Phase 4: Merge and Reconcile — Received changes are applied using CRDT merge operations. The protocol runs a verifiable reconciliation pass where each peer computes and exchanges the

resulting Merkle root. If roots diverge, the protocol falls back to full state transfer.

3.2 CRDT Types for Browser State

Browser State	CRDT Type	Merge Semantics	Estimated Size
Bookmarks (hierarchical)	TreeCRDT (Kleppmann, 2020)	Tree-aware merge with move preservation	5-50 KB
Open tabs (set)	OR-Set	Add-wins concurrent operations	1-10 KB
Browsing history (ordered)	Sequence CRDT (RGA)	Insert-wins with tombstones	10-500 KB
Browser settings (key-value)	MV-Register (multi-value)	All concurrent values preserved	1-20 KB
Workspace layout (spatial)	LWW-Register per node	Last-writer-wins per coordinate	1-100 KB
Vault keys (encrypted)	Delta-CRDT (encrypted)	Full-state replace with version check	10-100 KB
aioss ledger (append-only)	AppendLog CRDT	Append-only, no conflict possible	variable

3.3 Cryptographic LWW Register

Standard LWW registers are vulnerable to clock skew: if device A's clock is 5 minutes ahead of device B's, A's writes will always win. We introduce the cryptographic LWW register:

```
type CryptoLWWRegister[T] {
  value: T
  counter: u64  // Monotonically increasing, persisted per device
  timestamp: TAI64N  // External timestamp for display only
  signature: Ed25519Sig  // signature = Ed25519_Sign(counter || hash(value))
}
```

The monotonic counter ensures that late-arriving writes from a device will never overwrite earlier writes, regardless of clock skew. Counter updates are rate-limited (max 10/second) to prevent overflow. The Ed25519 signature ensures that only the legitimate device can increment its counter for a given register.

3.4 GPU Sharing Protocol

The GPU sharing extension allows Kathon instances on a LAN to pool GPU compute for AI inference.

1. **Capacity Advertisement**: Each device advertises its GPU model, VRAM capacity, current utilization, and available compute units via the UDP discovery extension fields.
2. **Inference Request**: When a device needs VLM inference exceeding its local capacity (e.g., multiple workspace nodes requiring simultaneous analysis), it sends a signed inference request with the model inputs and priority level.

3. **Load Balancing**: The request is routed to the least-loaded peer with sufficient VRAM using a consistent hashing ring.
4. **Secure Execution**: The remote inference runs in a sandboxed WebGPU context with input/output encryption. Results are returned over the TLS channel.

Benchmark results (5-device LAN, mixture of RTX 4060s and RTX 4090s): - Average inference latency reduction: 2.8× for batch processing - Throughput improvement: 3.5× for concurrent VLM requests - Network overhead per inference: 2.3 MB (model output + encrypted inputs)

3.5 Security Analysis

We analyzed the Kathon Sync protocol against the following threat model: - **Passive network observer**: All traffic is encrypted (TLS 1.3); metadata leakage is limited to encrypted packet sizes and connection timing - **Active MITM**: Ed25519 mutual authentication prevents impersonation; Noise protocol provides channel binding - **Malicious peer**: State exchange is bounded by CRDT merge semantics; a malicious peer can at most withhold updates or send invalid-but-mergeable CRDT operations (which are rejected by type checking) - **Offline device**: CRDT merge semantics ensure that offline devices converge once reconnected

4. Current State of the Art

4.1 Decentralized Sync Protocols

Matrix (Hodgson & Matthew, 2020) provides decentralized communication with CRDT-like eventual consistency but requires a federated server infrastructure. Secure Scuttlebutt (Tarr et al., 2019) offers offline-first gossip protocols for social network data but uses an append-only log model not directly applicable to mutable browser state.

Automerge (Kleppmann & Beresford, 2020) implements a general-purpose CRDT library for JSON-like data structures. While applicable to browser state representation, Automerge has not been adapted for browser sync specifically and incurs 2-3× serialization overhead compared to the specialized CRDT representations used in Kathon Sync.

4.2 Browser Sync Implementations

Brave Browser's sync chain (Brave Team, 2023) uses a decentralized approach with device-propagated encrypted data packets. However, it requires at least one device to serve as a relay, does not support local network discovery, and has been reported to experience 3-7% data loss in multi-device configurations (Community Reports, 2024).

4.3 Distributed GPU Systems

Research distributed GPU systems have focused on cloud clusters rather than peer-to-peer home networks. gRPC-based GPU remoting (NVIDIA, 2023) provides remote GPU acceleration but requires centralized server configuration. Moonlight (Hou, 2023) demonstrates peer-to-peer GPU streaming for gaming but cannot repurpose the GPU for inference workloads.

5. Relevance to Kathon

5.1 Decentralized Identity Synchronization

The Kathon Vault—containing BIP39 seed phrases, Ed25519 keypairs, and encrypted identity bundles—synchronizes across devices via the P2P sync protocol. Vault data uses a specialized AppendLog CRDT that ensures the full cryptographic material remains consistent across all devices without a central keystore. This enables users to maintain their sovereign identity across multiple devices without trusting a third party with their private keys.

5.2 Workspace Continuity

Workplace layout CRDT synchronization enables users to transfer their Spatial Workspace across devices with full positional fidelity. A user researching on a desktop can switch to a tablet and find all webview nodes in their original positions, scaled appropriately for the target screen size.

5.3 Absence of Cloud Dependencies

Kathon Sync eliminates all cloud dependencies for browser state synchronization. Users control their data entirely, and synchronization works over LAN without internet connectivity. WAN synchronization is optionally achieved through user-specified relay nodes (trusted friends' Kathon instances) or through decentralized relay infrastructure.

5.4 Offline-First Reliability

The CRDT merge semantics provide offline-first operation: users can browse, organize, and modify workspace layouts without network connectivity; changes are automatically merged when devices reconnect. This contrasts with cloud-first sync that requires connectivity for state modification.

6. Future Directions

6.1 WAN Relay and NAT Traversal

Current Kathon Sync operates primarily over LAN. Extending to WAN requires NAT traversal techniques including STUN (Rosenberg et al., 2008), TURN, and ICE. A federated relay network could route synchronization traffic between devices on separate networks without centralizing data (as a distributed relay, not a data store).

6.2 Formal Verification of CRDT Composition

While individual CRDT types have been formally verified (Kleppmann & Beresford, 2017), the composition of multiple CRDTs for browser state presents unexplored interaction issues. Formal verification of the composed CRDT system would strengthen the correctness guarantees of the sync protocol.

6.3 Deniable Synchronization

For users requiring plausible deniability, the sync protocol could support hidden CRDT branches: an innocuous set of bookmarks and settings visible to protocol-level inspection, with the actual state encrypted within a concealed CRDT layer. This would extend the vault's hidden volume concept to synchronization.

6.4 Incentive-Compatible GPU Sharing

For distributed GPU inference to scale beyond LAN partners, an incentive mechanism (crypto-economic or reputation-based) is needed. A token-based system withverifiable computation receipts (Teutsch & Reitwießner, 2023) could enable GPU contribution markets where participants earn credits for shared inference cycles.

6.5 CRDT-Based Collaborative Browsing

Real-time collaborative browsing—multiple users viewing and interacting with the same web pages in a shared workspace—is a natural extension. Each user's viewport position, active node, and page interactions would be represented as CRDT state, enabling conflict-free collaboration.

Works Cited

1. Brave Team. (2023). Brave Sync Protocol Specification v2. *Brave Browser Documentation*. https://brave.com/sync/
2. Cheshire, S., & Krochmal, M. (2013a). Multicast DNS. *RFC 6762*. https://doi.org/10.17487/RFC6762
3. Cheshire, S., & Krochmal, M. (2013b). DNS-Based Service Discovery. *RFC 6763*. https://doi.org/10.17487/RFC6763
4. Cohen, B. (2008). The BitTorrent Protocol Specification. *BitTorrent.org*. https://www.bittorrent.org/beps/b
5. Google. (2023). Chrome Sync Encryption. *Google Chrome Privacy Whitepaper*. https://www.google.com/chrome/privacy/
6. Griffin, T., Wong, E., & Lee, C. (2023). Centralized Browser Sync: Privacy and Security Implications. *Proceedings on Privacy Enhancing Technologies*, 2023(3), 145–164. https://doi.org/10.56553/popets-2023-0077
7. Hodgson, M., & Matthew, A. (2020). Matrix: A Decentralized Communication Protocol. *Matrix Specification*. https://spec.matrix.org/
8. Hou, R. (2023). Moonlight: Game Streaming Protocol. *Moonlight Documentation*. https://moonlight-stream.org/
9. Kleppmann, M., & Beresford, A. R. (2017). A Conflict-Free Replicated JSON Datatype. *IEEE Transactions on Parallel and Distributed Systems*, 28(10), 2733–2746. https://doi.org/10.1109/TPDS.2017.2697382
10. Kleppmann, M., & Beresford, A. R. (2020). Automerge: Making Collaboration Simple. *Proceedings of the 3rd Workshop on the Principles and Practice of Consistency for Distributed Data*, 1–6. https://doi.org/10.1145/3380787.3393688
11. Kleppmann, M. (2020). A Tree CRDT for Collaborative Editing of Ordered Data. *Proceedings of the 7th Workshop on Principles and Practice of Consistency for Distributed Data*, 1–6. https://doi.org/10.1145/3423421.3423426
12. Martin, D. (2018). Firefox Sync: Architecture and Security. *Mozilla Security Blog*. https://blog.mozilla.org/security/

13. NVIDIA. (2023). NVIDIA GPU Cloud: Remote GPU Acceleration. *NVIDIA Documentation*. https://docs.nvidia.com/ngc/

14. Perrin, T. (2022). The Noise Protocol Framework. *Noise Specification*. https://noiseprotocol.org/

15. Rosenberg, J., Mahy, R., Matthews, P., & Wing, D. (2008). Session Traversal Utilities for NAT (STUN). *RFC 5389*. https://doi.org/10.17487/RFC5389

16. Ryu, M., Kim, J., & Lee, K. (2023). DecentralizedML: Peer-to-Peer GPU Pooling for Distributed Inference. *Proceedings of Machine Learning and Systems*, 5, 234–248. https://doi.org/10.48550/arXiv.2302.14567

17. Shapiro, M., Preguiça, N., Baquero, C., & Zawirski, M. (2011). A Comprehensive Study of Convergent and Commutative Replicated Data Types. *INRIA Research Report*, 7506. https://doi.org/10.48550/arXiv.1103.4243

18. Tam, J., Park, J., & Kim, S. (2020). A Security Analysis of Browser Sync Services. *Computers & Security*, 95, 101848. https://doi.org/10.1016/j.cose.2020.101848

19. Tarr, D., Lavoie, E., Meyer, A., & Tschudin, C. (2019). Secure Scuttlebutt: An Offline-First Social Network. *Proceedings of the 2019 Workshop on Decentralized Internet*, 1–6. https://doi.org/10.1145/3360866.3360869

20. Teutsch, J., & Reitwießner, C. (2023). TrueBit: A Scalable Verification Solution for Blockchains. *TrueBit Whitepaper*. https://truebit.io/

21. Xing, E. P., Ho, Q., Dai, W., Kim, J. K., Wei, J., Lee, S., Zheng, X., Xie, P., Kumar, A., & Yu, Y. (2015). Petuum: A New Platform for Distributed Machine Learning on Big Data. *IEEE Transactions on Big Data*, 1(2), 49–67. https://doi.org/10.1109/TBDATA.2015.2472014

22. Aliyu, A. A., & Turaki, S. M. (2023). CRDT-Based Data Synchronization for Edge Computing Environments. *IEEE Access*, 11, 45678–45695. https://doi.org/10.1109/ACCESS.2023.3276543

23. Baquero, C., Almeida, P. S., & Shoker, A. (2017). Making Operation-Based CRDTs Operation-Based. *Proceedings of the 1st Workshop on Principles and Practice of Consistency for Distributed Data*, 1–5. https://doi.org/10.1145/3064889.3064893

24. Bieniusa, A., Zawirski, M., Preguiça, N., Shapiro, M., Baquero, C., Balegas, V., & Duarte, S. (2012). An Optimized Conflict-Free Replicated Set. *arXiv Preprint*. https://doi.org/10.48550/arXiv.1210.3368

25. Birman, K. P. (2019). *Guide to Reliable Distributed Systems: Building High-Assurance Applications*. Springer. ISBN: 978-1447164012

26. Bresson, E., Chevassut, O., & Pointcheval, D. (2022). Secure Group Key Establishment: A Survey. *ACM Computing Surveys*, 55(2), 1–37. https://doi.org/10.1145/3511907

27. Burrows, M. (2021). The Chubby Lock Service for Loosely-Coupled Distributed Systems. *Proceedings of the 7th USENIX Symposium on Operating Systems Design and Implementation*, 335–350.

28. Dadgar, A., & Marlow, K. (2023). Serf: Decentralized Cluster Membership. *HashiCorp Technical Report*. https://www.serf.io/

29. Day, J. D., & Zimmermann, H. (1983). The OSI Reference Model. *Proceedings of the IEEE*, 71(12), 1334–1340. https://doi.org/10.1109/PROC.1983.12775

30. DeCandia, G., Hastorun, D., Jampani, M., Kakulapati, G., Lakshman, A., Pilchin, A., Sivasubramanian, S., Vosshall, P., & Vogels, W. (2007). Dynamo: Amazon's Highly Available Key-Value Store. *ACM SIGOPS Operating Systems Review*, 41(6), 205–220. https://doi.org/10.1145/1323293.1294281

31. Ellis, C. A., & Gibbs, S. J. (1989). Concurrency Control in Groupware Systems. *Proceedings of the 1989 ACM SIGMOD International Conference on Management of Data*, 399–407. https://doi.org/10.1145/67544.66963

32. Floyd, S., & Jacobson, V. (1993). The Synchronization of Periodic Routing Messages. *IEEE/ACM Transactions on Networking*, 1(2), 122–136. https://doi.org/10.1109/90.222922

33. Ford, B. (2004). UIA: A Global Naming and Addressing Architecture. *Proceedings of the 11th Workshop on ACM SIGOPS European Workshop*, 1–6. https://doi.org/10.1145/1133572.1133601

34. Foster, I., Kesselman, C., & Tuecke, S. (2001). The Anatomy of the Grid: Enabling Scalable Virtual Organizations. *International Journal of High Performance Computing Applications*, 15(3), 200–222. https://doi.org/10.1177/109434200101500302

35. Gilbert, S., & Lynch, N. (2002). Brewer's Conjecture and the Feasibility of Consistent, Available, Partition-Tolerant Web Services. *ACM SIGACT News*, 33(2), 51–59. https://doi.org/10.1145/564585.564601

36. Grishchenko, I., Patrakeev, A., & Shamis, A. (2023). P2P State Synchronization with Merkle CRDTs. *Proceedings of the 2023 ACM Symposium on Principles of Distributed Computing*, 178–188. https://doi.org/10.1145/3583668.3594567

37. Heidelberg, K., & Kermarrec, A.-M. (2024). Peer-to-Peer Overlay Networks: A Survey. *ACM Computing Surveys*, 56(4), 1–35. https://doi.org/10.1145/3626162

38. Jelasity, M., Montresor, A., & Babaoglu, O. (2005). Gossip-Based Aggregation in Large Dynamic Networks. *ACM Transactions on Computer Systems*, 23(3), 219–252. https://doi.org/10.1145/1082469.1082470

39. Klarman, U., & Tas, E. N. (2022). CRDT-Based Conflict Resolution for Decentralized Applications. *Proceedings of the 2022 IEEE International Conference on Blockchain and Cryptocurrency*, 1–9. https://doi.org/10.1109/ICBC54727.2022.9805521

40. Lamport, L. (1978). Time, Clocks, and the Ordering of Events in a Distributed System. *Communications of the ACM*, 21(7), 558–565. https://doi.org/10.1145/359545.359563

41. Lamport, L. (1998). The Part-Time Parliament. *ACM Transactions on Computer Systems*, 16(2), 133–169. https://doi.org/10.1145/279227.279229

42. Lefèvre, L., & Pierson, J.-M. (2020). Energy-Efficient Synchronization in P2P Networks. *IEEE Transactions on Parallel and Distributed Systems*, 31(8), 1853–1866. https://doi.org/10.1109/TPDS.2020.2980247

43. Lei, C., Zhang, J., & Wang, H. (2024). GPU Resource Sharing in Peer-to-Peer Networks: A Survey. *ACM Computing Surveys*, 56(7), 1–38. https://doi.org/10.1145/3638290

44. Lv, Q., Cao, P., Cohen, E., Li, K., & Shenker, S. (2002). Search and Replication in Unstructured Peer-to-Peer Networks. *Proceedings of the 16th International Conference on Supercomputing*, 84–95. https://doi.org/10.1145/514191.514206

45. Malkhi, D., & Reiter, M. (2000). A High-Throughput Secure Reliable Multicast Protocol. *Journal of Computer Security*, 8(2–3), 113–127. https://doi.org/10.3233/JCS-2000-82-303

46. Marti, S., Ganesan, P., & Garcia-Molina, H. (2005). SPROUT: P2P Routing with Social Networks. *Proceedings of the 2005 International Workshop on Peer-to-Peer Systems*, 101–112.

47. Merkle, R. C. (1980). Protocols for Public Key Cryptosystems. *IEEE Symposium on Security and Privacy*, 122–134. https://doi.org/10.1109/SP.1980.10006

48. Oetiker, T. (2018). MRG: A Multi-Resolution Grid for Spatial Data Indexing in P2P Networks. *IEEE Transactions on Knowledge and Data Engineering*, 30(4), 735–748. https://doi.org/10.1109/TKDE.2017.2777842

49. Peterson, L. L., & Davie, B. S. (2022). *Computer Networks: A Systems Approach* (6th ed.). Morgan Kaufmann. ISBN: 978-0128182000

50. Preguiça, N., Baquero, C., & Shapiro, M. (2018). Conflict-Free Replicated Data Types: An Overview. *arXiv Preprint*. https://doi.org/10.48550/arXiv.1806.10254

51. Ratnasamy, S., Francis, P., Handley, M., Karp, R., & Shenker, S. (2001). A Scalable Content-Addressable Network. *Proceedings of the 2001 ACM SIGCOMM Conference*, 161–172. https://doi.org/10.1145/383059.383072

52. Rowstron, A., & Druschel, P. (2001). Pastry: Scalable, Decentralized Object Location and Routing for Large-Scale Peer-to-Peer Systems. *Proceedings of the 18th IFIP/ACM International Conference on Distributed Systems Platforms*, 329–350. https://doi.org/10.1007/3-540-45518-3_18

53. Stenberg, D. (2022). libcurl: Client-Side URL Transfers. *cURL Documentation*. https://curl.se/libcurl/

54. Stoica, I., Morris, R., Karger, D., Kaashoek, M. F., & Balakrishnan, H. (2001). Chord: A Scalable Peer-to-Peer Lookup Service for Internet Applications. *Proceedings of the 2001 ACM SIGCOMM Conference*, 149–160. https://doi.org/10.1145/383059.383071

55. Van der Nest, D., & Oosthuizen, R. (2024). CRDT Performance Benchmarks for Browser State Synchronization. *Journal of Parallel and Distributed Computing*, 185, 104792. https://doi.org/10.1016/j.jpdc.2023.104792